Galactic Cosmic Ray Astrophysics

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Highly energetic particles constantly enter the Earth's atmosphere from space! The centenary of this startling discovery was celebrated in 2012, but answers to many of the most basic questions regarding cosmic rays (an historic misnomer) are still surprisingly uncertain. Cosmic rays (CR) are charged particles with spectra spanning over 13 orders of magnitude in energy and falling by factors of ~50 per decade. CR energy density is comparable to starlight, galactic magnetic fields, and the kinetic energy of the ISM. They are the richest source of information on the chemical evolution of the galaxy and probe some of the most extreme environments and exotic processes in the universe. CR have been detected at $>10^{20}$ eV (separate abstract). To $\sim10^{17}$ eV, CR originate in the galaxy. Then, an extragalactic component enters and dominates above $\sim10^{18}$ eV. In stark contrast to photons, CR are isotropized by intergalactic, galactic, and heliospheric magnetic fields, except at the highest energies and do not point back to sources. CR are central components of the dynamics of the galaxy and broader universe, and **a comprehensive program of CR studies must be a part of any NASA Roadmap**.

Most galactic CR (GCR) are atomic nuclei, mainly H but including all elements through actinides. GCR nuclei are most likely accelerated in SNR (c.f. recent Fermi-LAT results), and their elemental and isotopic compositions probe nucleosynthesis, nuclear interactions with the ISM, the distribution of freshly synthesized elements, and acceleration processes. Secondary GCR nuclei, e.g. Li, Be, B, and sub-Fe elements, are produced by fragmentation of more abundant nuclei in the ISM or the wall of the local bubble. Stable secondary/primary ratios, e.g. B/C and sub-Fe/Fe, measure the material traversed by the GCR. Radioactive secondary GCR, e.g. ^{10}Be, ^{26}Al, ^{36}Cl, ^{54}Mn, and ^{14}C, are "clocks" that probe GCR age and the fraction of time in the galactic halo. Other radioactive isotopes, such as ^{59}Ni, decay by e^- capture and give the time between nucleosynthesis and acceleration. Trans-Fe elements and isotopes like ^{22}Ne probe GCR nucleosynthesis sites and selection for acceleration. At energies above the influence of the solar wind, the all-particle GCR nuclear spectrum falls at $\sim E^{-2.7}$ to $\sim10^{15}$ eV where the spectrum steepens (the " knee") to $\sim E^{-3.1}$ commonly attributed to failure of the supernova acceleration mechanism. Higher GCR energies may result from magnetic feedback "amplification" of the SN shocks by the GCR themselves.

GCR also include electrons, positrons, and antiprotons. Most result from interactions of GCR nuclei with the ISM, but other origins are possible. Positrons and electrons can be produced in objects such as pulsars or SNR, and deviations in their spectra can provide important insights into nearby sources. Particles and antiparticles may also be produced by the annihilation of dark-matter (DM) candidates (neutralinos or Kaluza-Klein particles) and spectral details provide important DM constraints. Composite antinuclei are possible as relics of the big bang or, in the case of antideuterons, produced in DM annihilation. No composite antinuclei have been detected.

The (e^-+e^+) spectrum falls as $\sim E^{-3}$ and softens rapidly above ~1 TeV. Electrons lose energy quickly, and any detected with ≥TeV energy must have originated within $\sim10^5$ yrs and from ≤ a few hundred pc. Above 1 TeV, features from discrete sources might be visible. A significant feature < 1 TeV might also indicate a nearby source of electrons, a pulsar or, perhaps, a DM clump. The positron spectrum ≥10 GeV shows significant excess over expected secondary production, possibly from similar sources.

Most cosmic-ray antiprotons are secondaries produced by interactions of GCR with the ISM. Production kinematics and the energy spectra of the primary cosmic rays give a characteristic secondary antiproton spectrum with a peak around 2 GeV and sharp decreases below and above the peak. The presence of an additional source like DM annihilation or primordial black hole evaporation might be seen as a deviation from the secondary spectrum above or below the peak.

All CR species from nuclei to antimatter can be measured using technologies that are very well developed both in astrophysics and in accelerator nuclear and particle physics. There are no true general-purpose instruments; e.g. antiparticles require magnets to measure charge sign, higher energies require calorimeters, etc. With some important exceptions, the bulk of CR data has been obtained with great success by balloon-borne instruments. However, rare CR species, such as antiparticles and ultra-heavy elements, and high energies ("knee" and above) require the exposure offered by spaceflight. Lacking is a comprehensive program supporting these measurements. This must be a part of the NASA roadmap.